

# Improved Gate Reliability Normally-Off p-GaN/AlN/AlGaIn/GaN HEMT with AlGaIn Cap-Layer

Chia-Hao Liu<sup>1</sup>, Hsien-Chin Chiu<sup>1</sup>, Hsiang Chun Wang<sup>1</sup>, Hsuan Ling Kao<sup>1</sup>, Chong Rong Haung<sup>1</sup>

<sup>1</sup>Department of Electronics Engineering, Chang Gung University, Taiwan, R.O.C.

TEL: +886-3-2118800 # 3645

Email: [hcchiu@mail.cgu.edu.tw](mailto:hcchiu@mail.cgu.edu.tw)

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## Abstract

In this work, the dual junction-high-electron-mobility-transistor (DJ-HEMT) was investigated. The thin AlGaIn was grown between the p-GaN gate and gate metal. In the TCAD simulations, the band gap and electric field were shown in this letter, proving the dual junction forming. Moreover, DJ-HEMT shows the high gate voltage swing due to the dual junction at the gate region of device, which enhance gate performance. By contrast with standard p-GaN HEMT (ST-HEMT), DJ-HEMT shows higher  $V_{TH}$  of 2V, saturation current of 187mA/mm,  $I_{ON}/I_{OFF}$  ratio of  $5.1 \times 10^8$  and gate swing voltage which is higher than 20V. In addition, DJ-HEMT also shows the lower device leakage current and superior life time measurement due to the thicker and higher barrier of AlGaIn cap layer.

## INTRODUCTION

GaN based power devices are emerging as promising candidates for the next generation power switching application due to their wide band gap, high mobility and high electric breakdown field. Conventional p-GaN gate HEMT can be modeled as two back-to-back diodes at the gate region, a reverse Schottky junction and a forward p-n junction, under the forward bias. However, back-to-back diode make the p-GaN gate HEMT operate more than 10V, but the gate bias allowed for long-term reliable operation is approximately 7~8V due to the degradation of the reverse Schottky diode induced by gate leakage current under the high electric field [1]. According to the result, in power switching application, p-GaN gate HEMT need a large threshold voltage and large gate swing voltage to prevent false turn on in high-frequency power switching and make them match with the gate drive circuit design.

The gate failure of p-GaN HEMT has been attribute at the interface between the gate metal/p-GaN layer and/or the p-n junction at p-GaN/AlGaIn/GaN region under the high electric field. Moreover, the time-dependent gate breakdown (TDGB) behavior exhibits a high temperature coefficient, causing the impact ionization and carrier injection under the high electric field [2]. When the high positive bias occurring at long stress, the defects were thermally active created by hot holes. Because of the impact ionization mechanism occurring, hot holes can be generated and then accelerated to the AlGaIn barrier. Furthermore, the holes release their energy to the lattice and then create the defects at the AlGaIn layer or the

interface between the p-GaN/AlGaIn layer [3].

Hence, we propose a AlGaIn/p-GaN/AlGaIn/GaN HEMT to improve the gate performance and suppress the leakage current. The AlGaIn cap layer not only as the barrier layer to prevent the carrier injection behavior but also forming a junction with p-GaN layer. Finally, the Schottky diode/Junction1 (J1)/Junction2 (J2) at gate region was investigated as a new structure in the p-GaN HEMT.

## EXPERIMENTAL PROCEDURES

In this work, the AlGaIn/p-GaN/AlN/AlGaIn/GaN HEMT was grown on 6-inch Si (111) substrates by MOCVD. For the cross-sectional schematic of the epi structure was shown in Fig. 1(a), a 300 nm thick undoped GaN channel layer was grown on top of 4  $\mu$ m thick undoped AlGaIn/GaN buffer/transition layer. Moreover, there are two AlN layer designed in this structure, one is spacer layer and another one is for etching stop layer. Afterward, a 15 nm thick  $Al_{0.23}Ga_{0.77}N$  layer and a 100 nm thick p-type GaN layer were grown. Finally, a 10 nm thick  $Al_{0.2}Ga_{0.8}N$  was grown on the p-GaN layer, trying to form a junction there, as shown in the structure by TEM. For the device fabrication, the p-GaN etching of  $Cl_2/BCl_3/SF_6$  based inductively coupled plasma and the AlN layer as an etching stop layer. The ohmic contacts were prepared by electron beam evaporation and Ti/Al/Ni/Au (25/120/25/150 nm) were stacked on the device sequentially. Then, both devices were annealed by RTA system at 875 °C for 30 s in  $N_2$  ambient. Finally, a Ni/Au (25/120 nm) gate metal stack is deposited and 100 nm of SiN was passivated.

However, the benefits of such an AlGaIn cap layer could be explained by band diagram in Fig. 1(b). When the large positive bias stress at the gate side, the Schottky metal/p-GaN diode is reversed bias, further extending the depletion region, and the electrons in the channel might be emitted over the AlGaIn barrier and injected into the p-GaN Layer. Once the electrons transfer to the p-GaN region, they can be accelerated by a high electrical field in the depletion region, yielding impact ionization. Besides, the hole injection is occurring, and the holes drift in the p-GaN layer towards the p-GaN/AlGaIn heterointerface and recombine with the injected electrons. Moreover, the injection holes may be a trap state in AlGaIn/GaN heterostructure. Thus, the AlGaIn cap layer stacked on the p-GaN not only be a barrier but also form a depletion region, suppressing the carrier injection behavior.

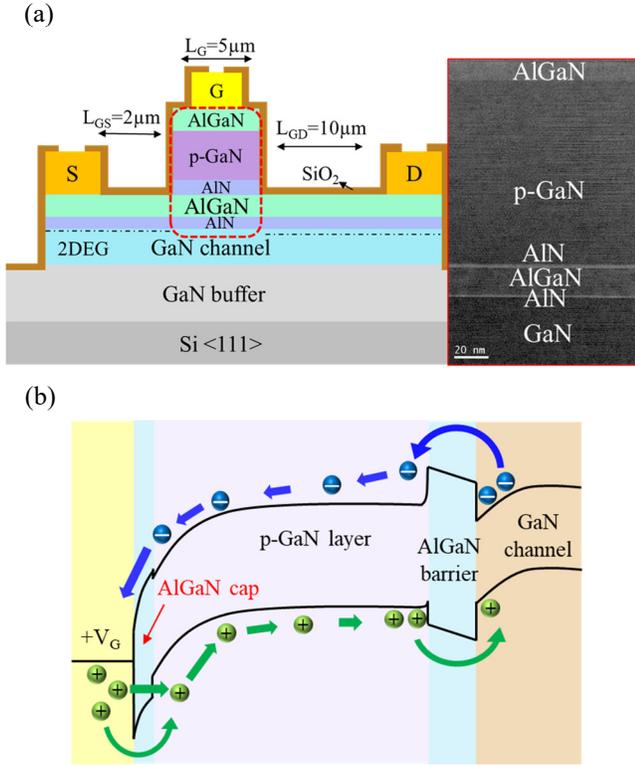


Fig. 1(a) Cross sectional schematic of p-GaN gate HEMT, (b) the band diagram of DJ-HEMT under the large positive gate voltage.

## RESULTS AND DISCUSSION

To prove the dual junction structure, the electric field was simulated by TCAD system, as shown in Fig 2. When the device is under the original state, two electric field distribute at the top side and bottom of p-GaN layer. Therefore, there are two junctions forming at gate region which are Junction1 (J1) and Junction2 (J2). Comparison with Schottky diode of ST-HEMT, the junction1 can suppress the carrier injection, and the thicker and higher barrier height may increase gate operation voltage.

Fig 3(a) and (b) shows the log-scale transfer ( $I_{DS}-V_{GS}$ ) and output ( $I_{DS}-V_{DS}$ ) characteristics of DJ-HEMT and ST-HEMT. As shown in Fig3(a), the off-state current for the DJ-HEMT and ST-HEMT were  $3 \times 10^{-7}$  and  $2.2 \times 10^{-6}$  mA/mm, respectively, at  $V_{GS} = 0$  V. Additionally, the threshold voltage ( $V_{TH}$ ) value for the DJ-HEMT and ST-HEMT were 2 V and 0.6 V, respectively. The corresponding maximum drain current density ( $I_{Dmax}$ ) values were 116 and 187 mA/mm, respectively.

To analyze the effect of the J1,  $I_{GS}-V_{GS}$  measurement was shown in Fig4(a). DJ-HEMT exhibits the large gate operation voltage, and the lower gate leakage current under the forward bias. In this work, the gate turn on voltage ( $V_{GS\_ON}$ ) was defined at  $I_{GS}=1$  mA/mm, which are 8.2V and larger than 20V of ST-HEMT and DJ-HEMT, respectively. Moreover, when

the  $V_{GS}$  operate at off state and/or small bias, DJ-HEMT showing the lower leakage current, the J1 prevent the hot electrons emitted from channel to gate side. Besides, this figure also shows two solid fitting lines and they intersect at  $V_{GS}=16$  V. It indicates the hole injection behavior is occurring and increase the gate leakage current [4]. As the results, the AlGaN cap like a barrier which suppress the hole injection behavior efficiently. In Fig4(b), the Off-state breakdown voltage of two devices were measured by Agilent B1505, and the DJ-HEMT shows the higher Off-state breakdown voltage owing to lower leakage current.

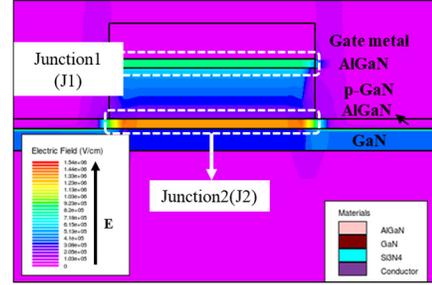


Fig. 2 Distribution of electric field of gate region by TCAD simulation.

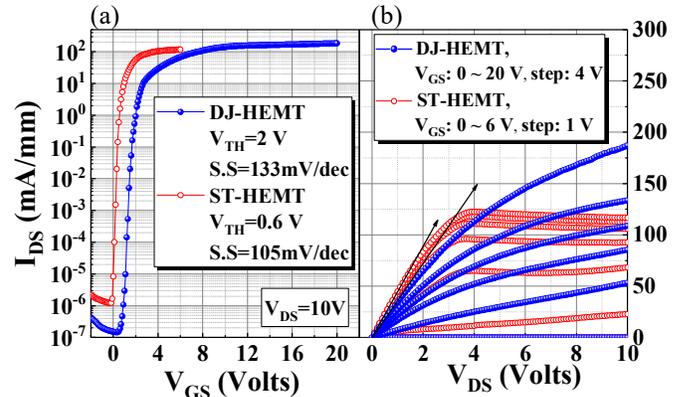


Fig. 3. DC characteristics of DJ-HEMT and ST-HEMT with  $L_{GS}/L_G/L_{GD}/W_G = 2/5/10/100$   $\mu$ m. (a) Transfer characteristic. (b) Output characteristic.

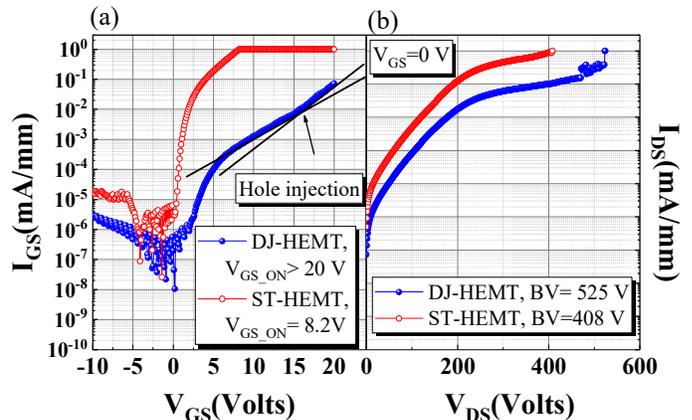


Fig. 4. (a)  $I_{GS}-V_{GS}$  characteristic and (b) Off-state breakdown voltage measurement of DJ- and ST- HEMTs.

The aim in this work is to enhance the gate performance, so we use TDGB measurement, Weibull distribution and failure of life time to assess the gate reliability DJ-HEMT, which are shown in Fig5(a), (b), (c). In this measurement, the gate failure value is defined at  $I_{GS}=1\text{mA}/\text{mm}$ , and there is no bias applied on drain side. As the result, the gate was applied under three different voltages (17V, 18V, 19V). The gate current was in the lower order at the initial state due to the accumulated negative charges under the gate, so the gate leakage current was suppressed. Then, the gate leakage current becomes noisy due to the percolation path has formed. However, the gate dielectric hard breakdown occurs, which shows a sudden increase of the gate leakage current afterwards which was based on the reference of the percolation path formation [5]. After that, the Weibull distribution was plotted by calculating and the failure rate of 63.2% can be calculated of 10.8V and the slope are tight distribution and less variability. However, Fig5(d) shows the comparison of gate breakdown voltage and gate leakage current at  $V_{GS}=6\text{V}$ . Finally, DJ-HEMT exhibits the better gate performance and compared with each group [6-11].

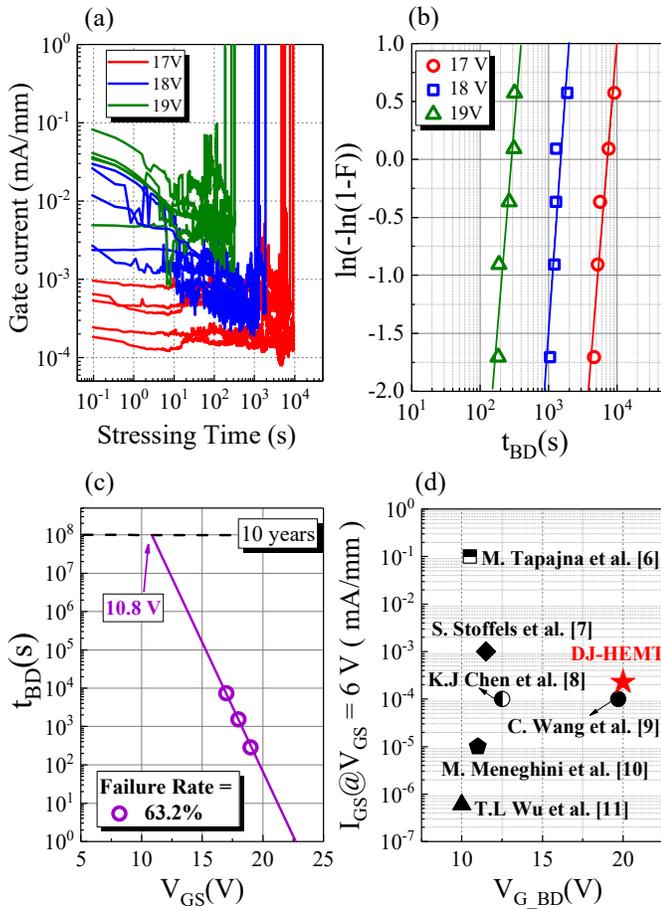


Fig. 5. (a) TDGB measurement, (b) Weibull plot of the time-to-breakdown distributions. (c) lifetime prediction with failure rate of 63.2% of DJ-HEMT. (d) Comparison with other team of the gate breakdown voltage and leakage current.

## CONCLUSIONS

A normally-off p-GaN HEMT with AlGaIn cap was investigated in this work. The hot electron and hole injection are suppressed by Junction1 and AlGaIn cap, respectively. The device exhibits better DC characteristic, Off-state breakdown voltage, and gate reliability owing to the dual junction gate which reduced the leakage and enlarge forward gate breakdown voltage, paving the way to higher reliable GaN power devices.

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